Retracking CryoSat waveforms for Near-Real-Time ocean forecast products and platform attitude

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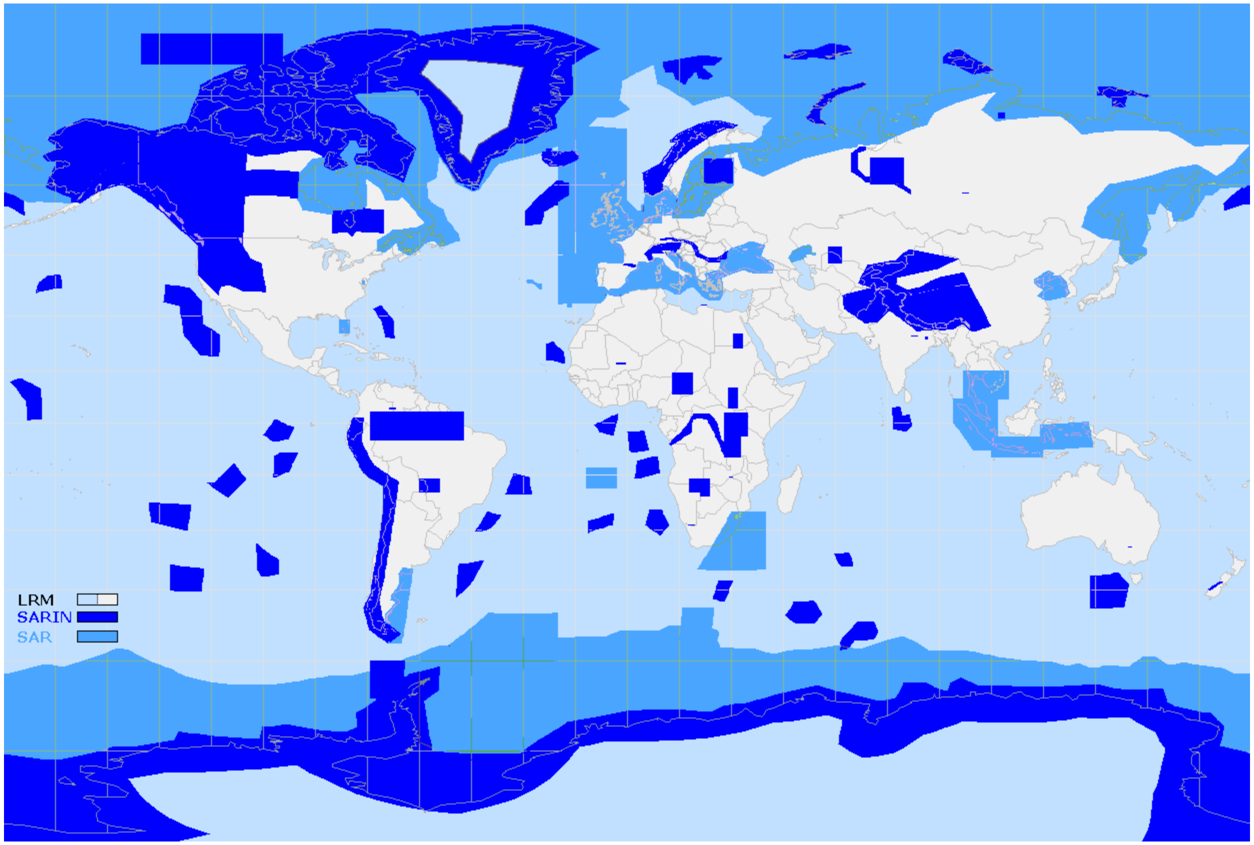
CryoSat-2 LRM Mode Products



- LRM (Low Rate Mode) = Operates as a conventional altimeter.

LRM Products:

- FDM (Fast Delivery Mode) = short latency, DORIS DIODE or predicted orbit, predicted meteo & ancillary data.
- "LRM" = Final version, precise orbit, analyzed meteo, etc. (final "GDR").

Level L1b = Has waveform and geophysical corrections, but no derived quantities (range, SWH, σ^0) ➔ no sea surface height, wind speed (U_{10}), wave height, backscatter, etc.

Level 2 = No waveform; has geophysical corrections and derived quantities.

We build all our results from LRM L1b FDM waveform products.

Fast Wind & Wave Recipe

① Download new FDM L1b data from ESA ftp server.
② Retrack* the waveforms at 20-Hz.
③ Average the 20-Hz results to 1-Hz.
④ Remove land values and reformat SWH and U_{10} for NOAA's forecasters (N-AWIPS).
⑤ Export to NOAA forecasters via NOAA ftp sites.

SWH requires only a waveform and lat,lon.
σ_0, to within ± 1dB, requires only AGC and lat,lon.
Retracking and (crude) orbit height improve σ^0.
Nothing else needed for SWH and σ^0, U_{10}.

*Our retracker can replicate MLE3, MLE4, RED4, etc. as desired. It assumes a circular antenna pattern using the azimuthally averaged beamwidth of CryoSat's elliptical antenna pattern [Wingham & Wallace, 2010].

Speed & Latency

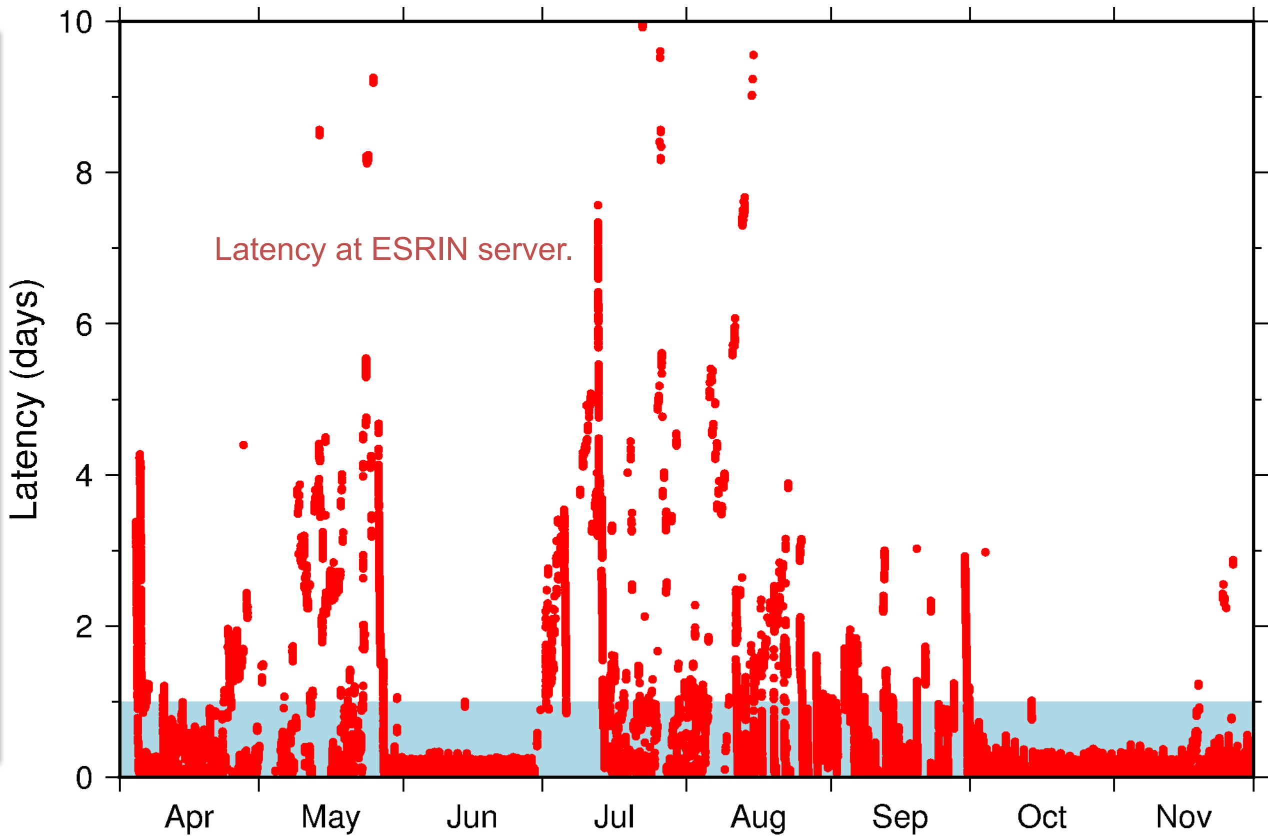
Every hour, we search ESA ESRIN ftp site for new FDM L1B data.

From ESRIN ftp to NOAA N-AWIPS, our process takes about 2 minutes, end-to-end. Thus latency is determined on the ESA side.

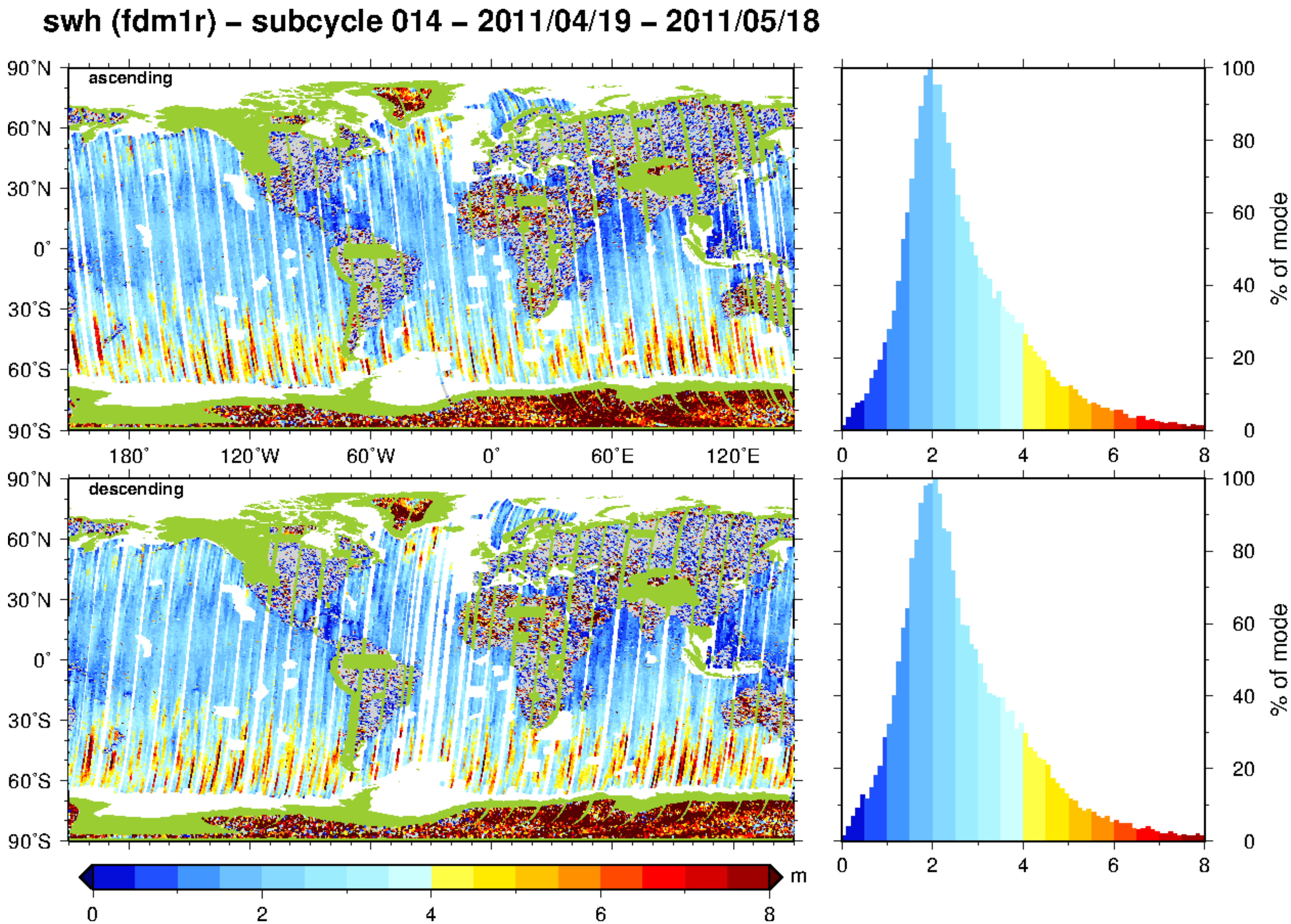
Latency = Arrival time ESRIN server – Time of first measurement

Until recently, less than 25% of FDM L1B files were available within 3 hours of real time.
This has now improved.

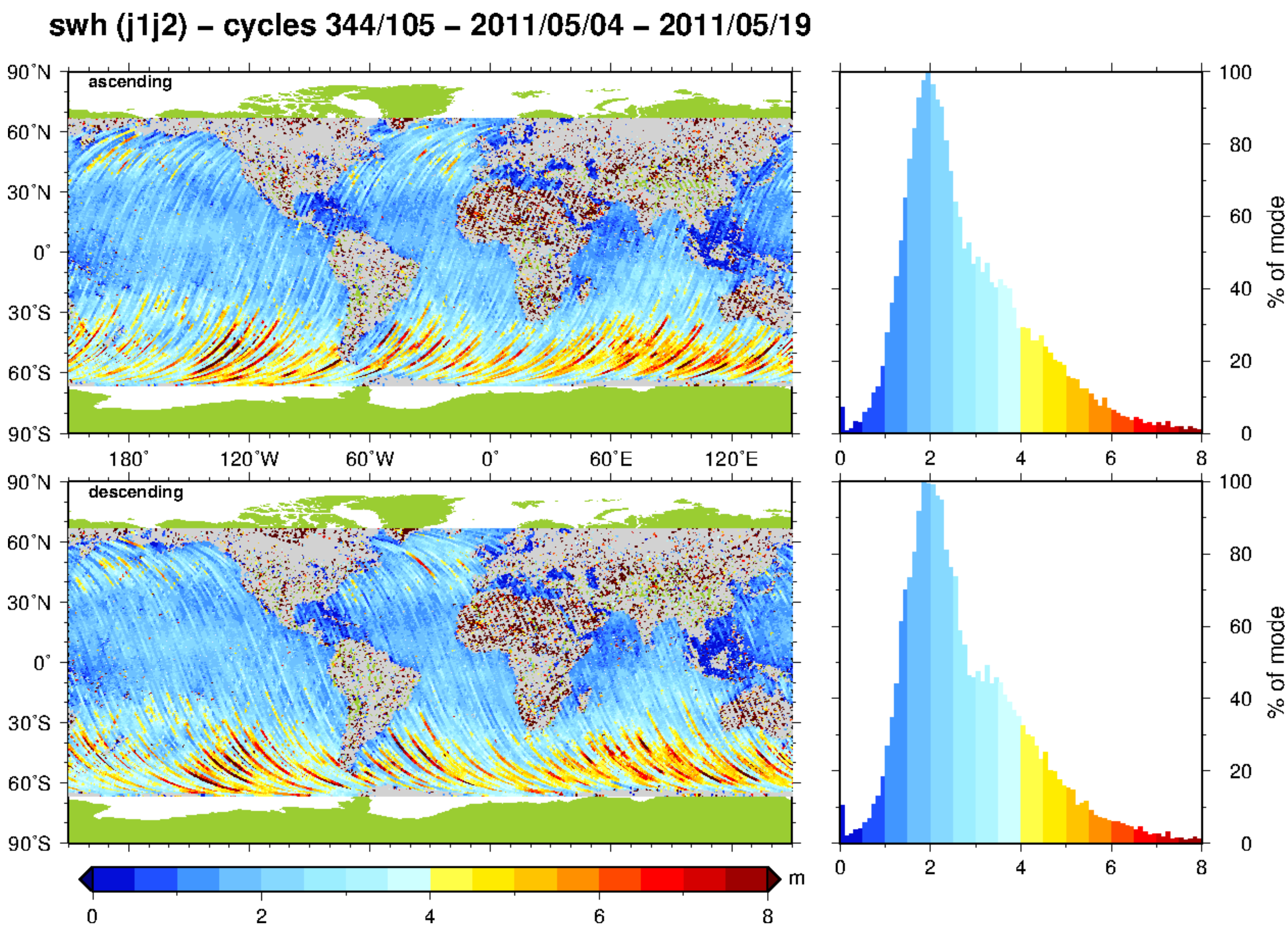
October and November:
67.7% within 3 hours;
86.2% within 6 hours;
99.6% within 24 hours.



CryoSat2 Wave Heights



Jason-1 & -2 Wave Heights



Wind speed is not as easy as wave height.

Retracking yields SWH straightforwardly.

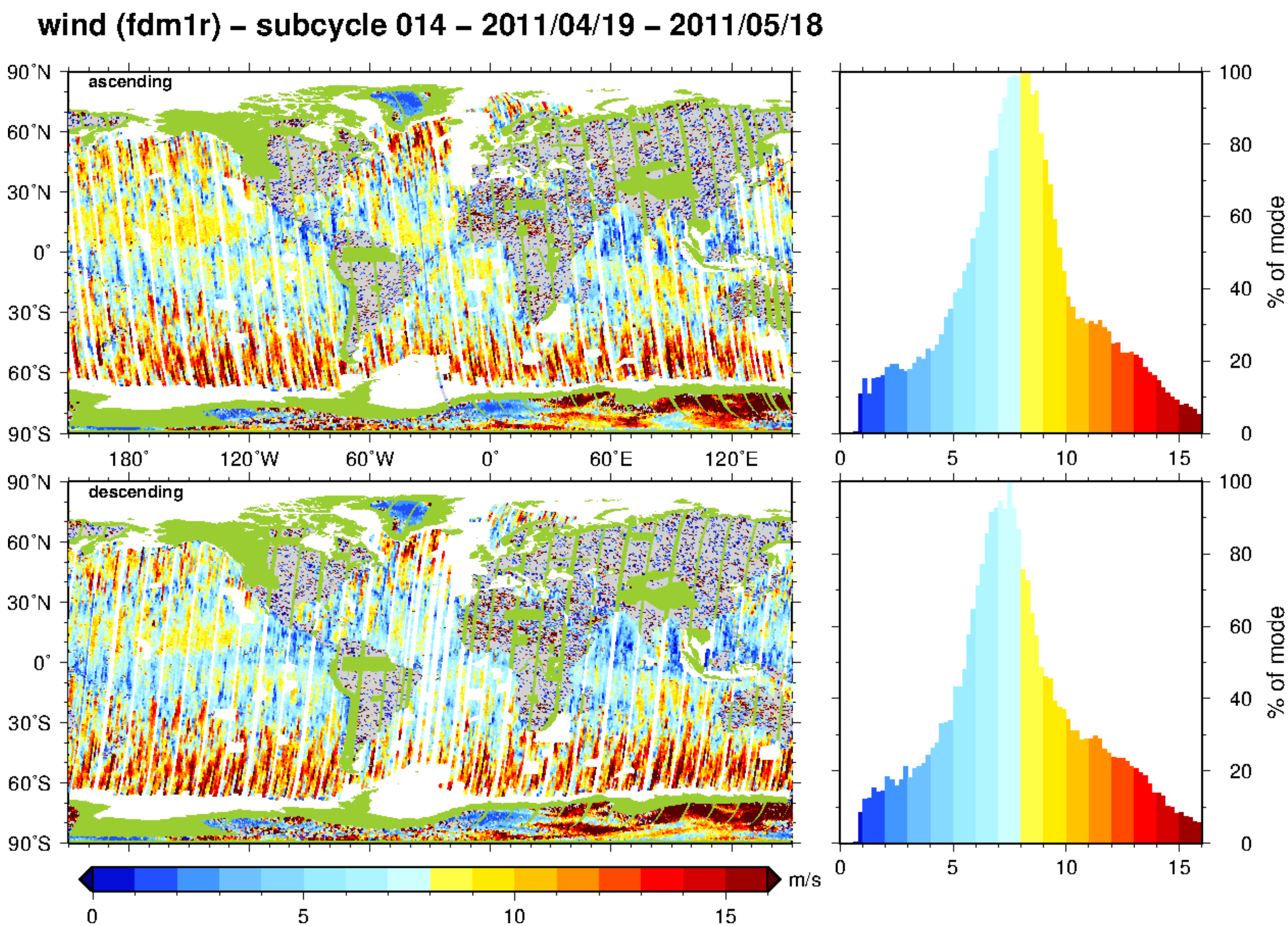
Wind speed is estimated from backscatter, σ^0, by empirical models tuned separately for each altimeter. *<u>We don't yet have a model for CS2.</u>*

σ^0 can be obtained by retracking, but there is an unknown (to us, at least) constant, representing $10*\log_{10}$ of the system gains and losses.

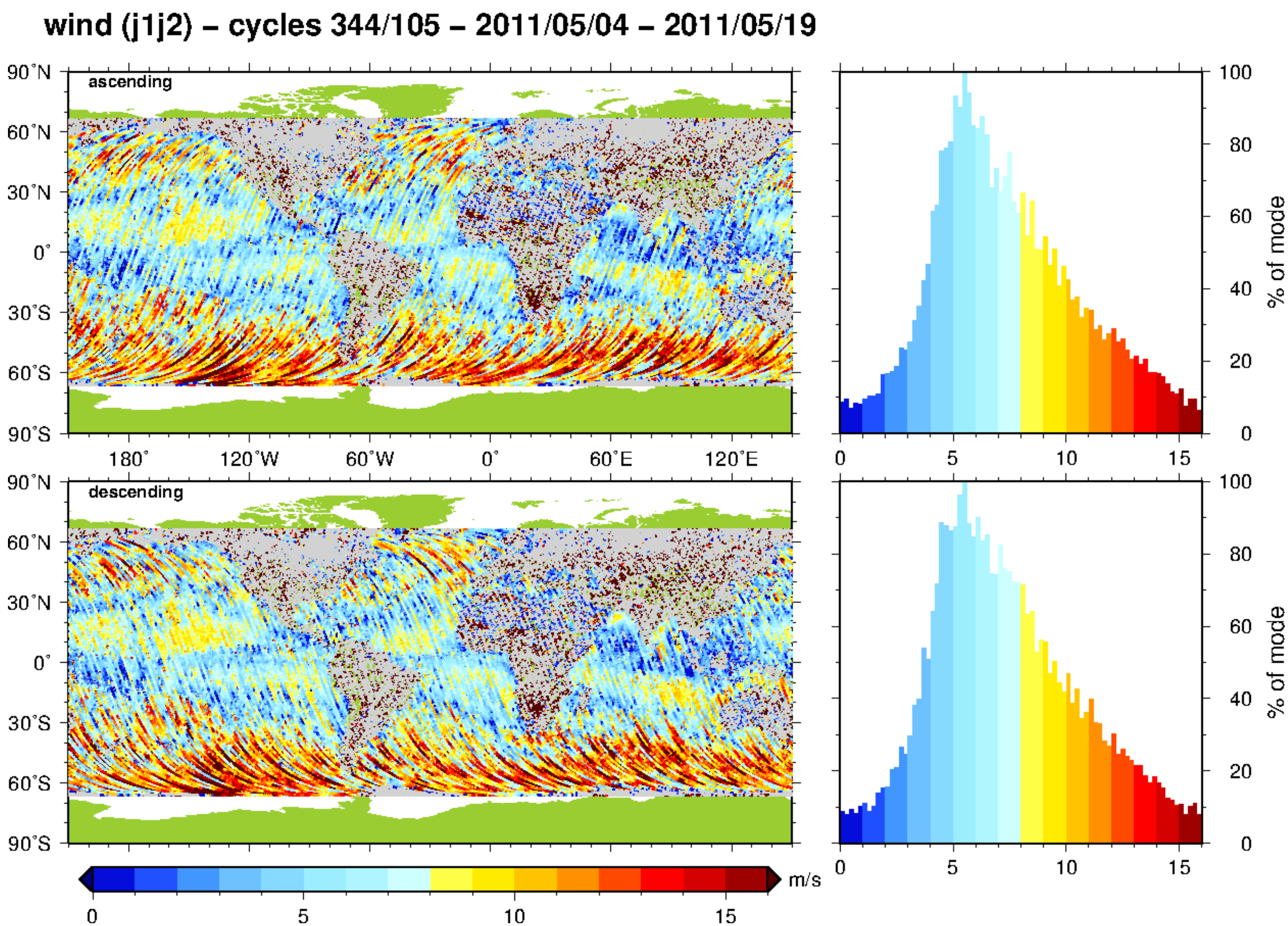
<u>We had to guess this unknown constant.</u>

Our wind speed estimates are therefore *ad hoc* and preliminary. (Envisat model used in next slide.)

CS2 Wind Speeds (Abdalla model)



J-1 & -2 Wind Speeds (Collard model)



NOAA CS2 LRM I-GDR

We would like accurate sea surface height anomalies within ~3 days of real time for Ocean Heat Content, Surface Currents, and other applications. We are building that using our LRM FDM waveform retracker and RADS:

✓Orbit: DORIS MOE* from CNES and ESA

✓Iono: GPS GIM

✓Meteo: NOAA NCEP (ECMWF request pending)

✓IB: MOG2D

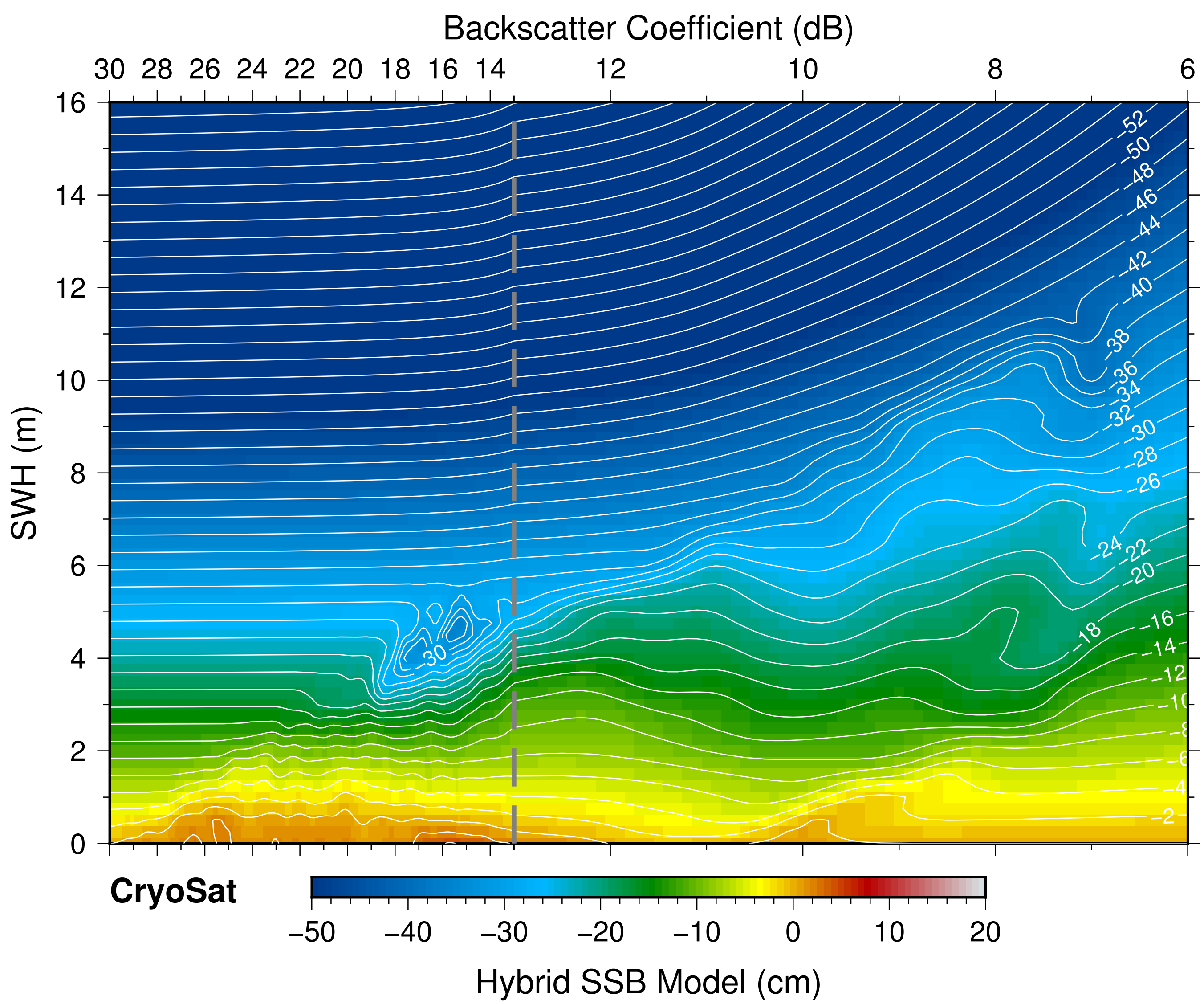
✓Tides: FES, GOT

✓SSB: Empirical hybrid model fit to SSH anomaly data.

We will distribute this through RADS to interested users.

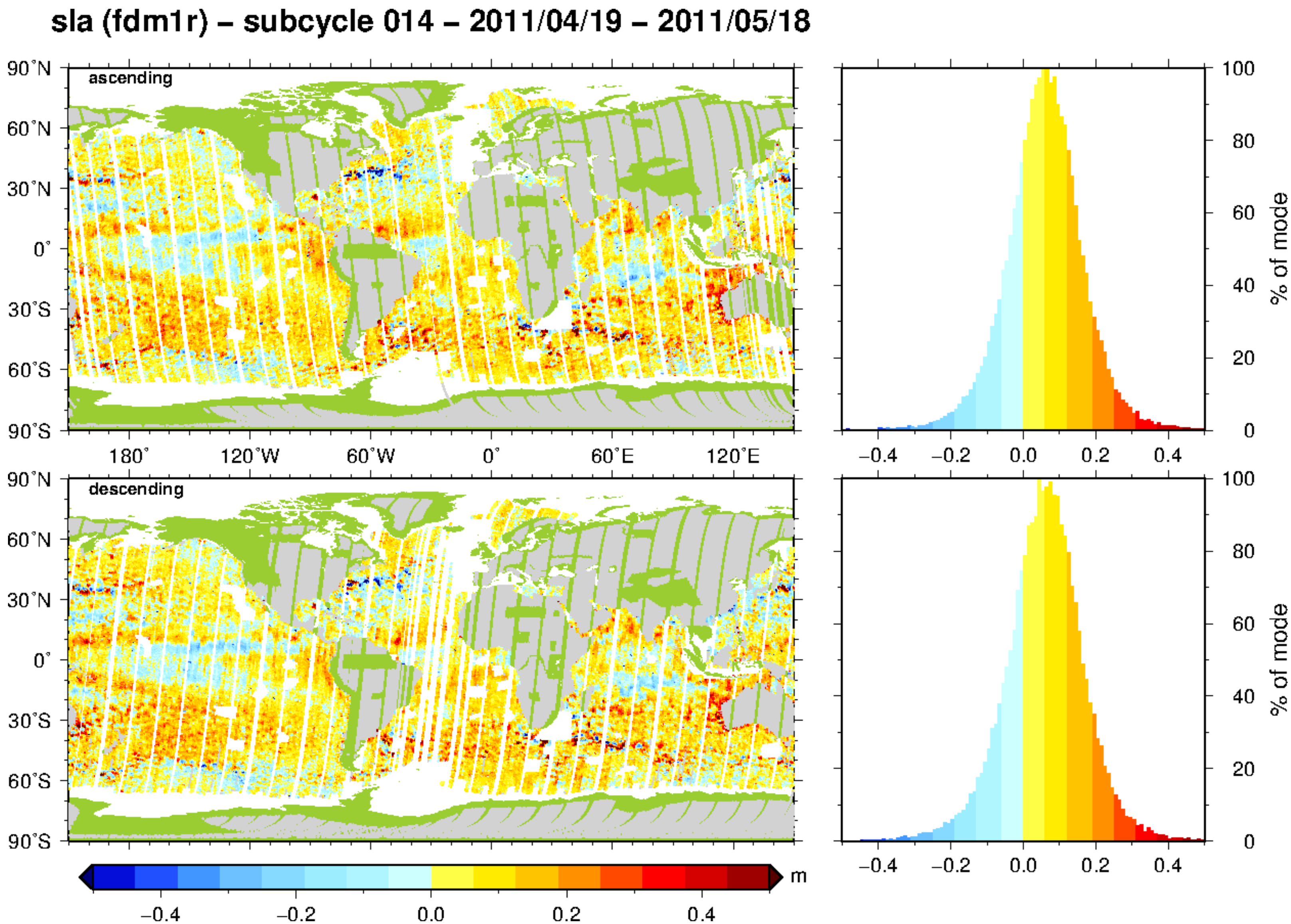
*The orbits supplied on the FDM are not suitable. They jump between predicted and real-time orbit ephemerides, with different interpolation bugs, and consequently jump in range error, timing bias, and apparent platform pitch error.

CS2 SSB is typically -3.5% SWH

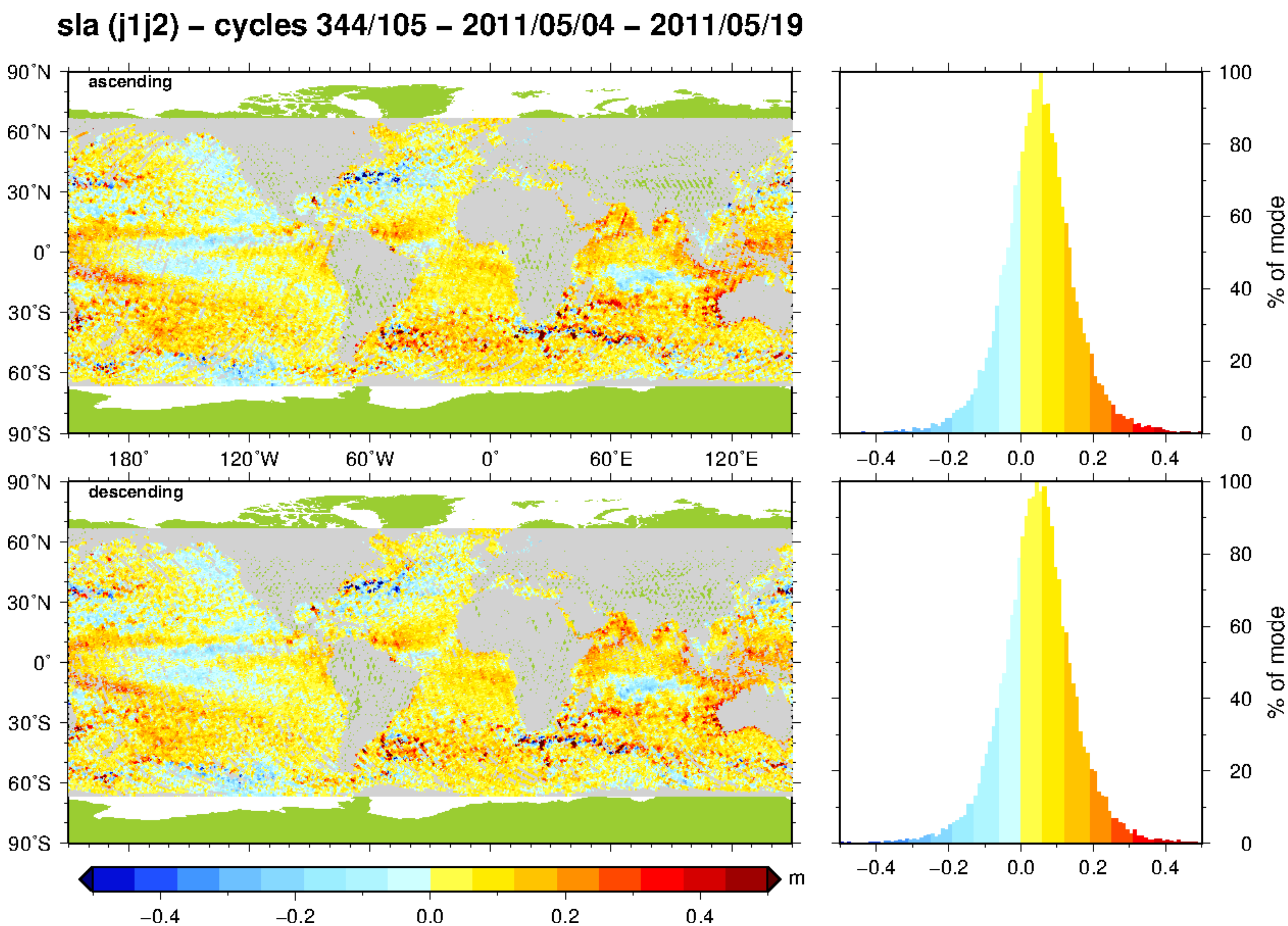


Direct Method; BM-4 style; relative to DTU10 Mean Sea Surface; fit to subcycles 11-17

CS2 Sea Level Anomaly



J-1 & J-2 Sea Level Anomaly



SSH crossovers < 3 days

	Mean (mm)	Std. Dev. (mm)
Env – Jason-2	-2.8	48.9
CS2 – Jason-2	+0.2	50.8
CS2 – Env	-2.4	49.7

CryoSat2 seems as good as J-2 and Envisat

Platform attitude: Why?

We would like to supply the off-nadir mispointing of the antenna's boresight as a known value in the retracking, and thus use an "MLE3"-like retracker.
This reduces noise in the estimated quantities.

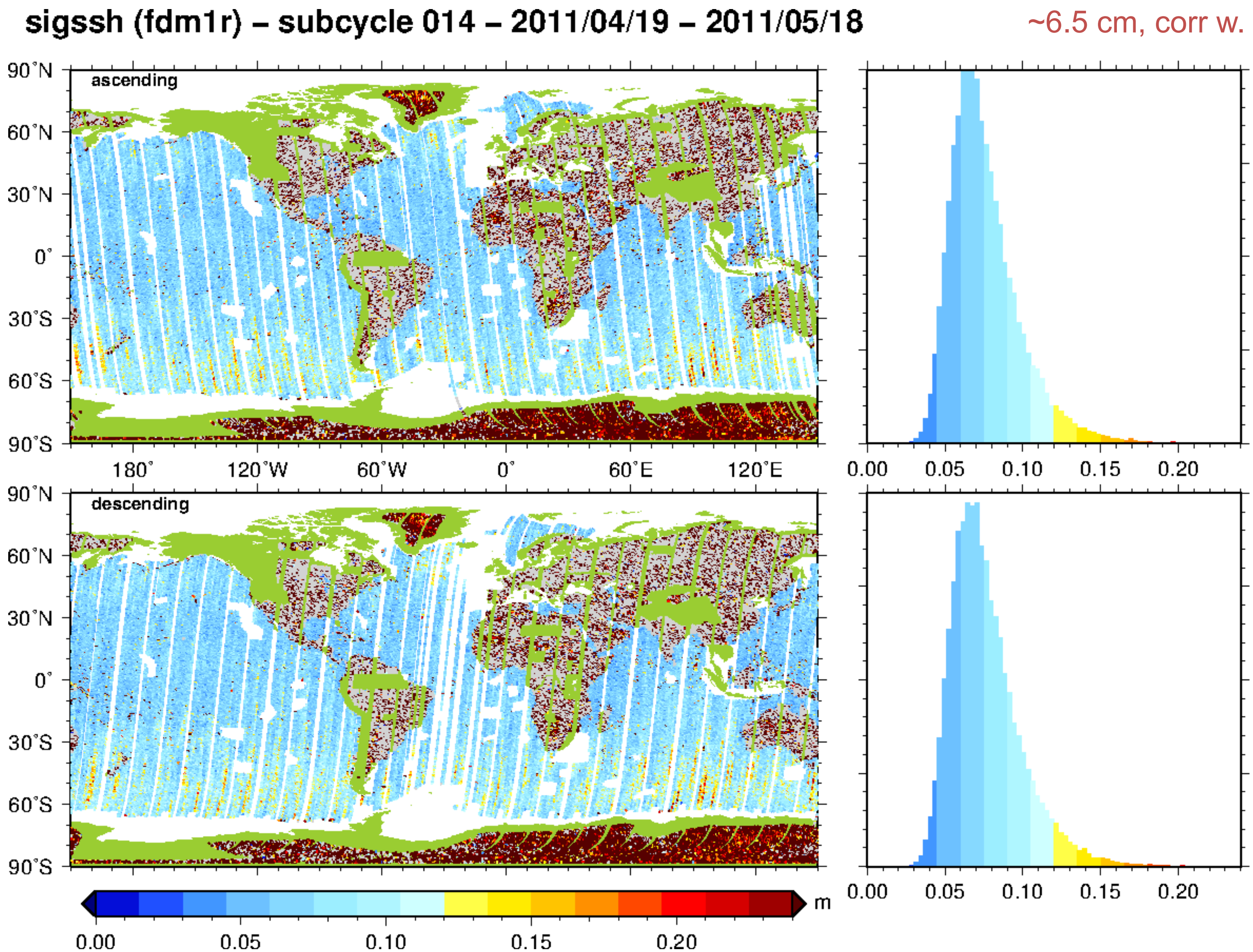
If we have to treat the off-nadir angle as an unknown and leave it free to be fitted ("MLE4"-like), then additional waveform noise couples into noise in sea surface height, wave height, and wind speed estimates.

Further, when MLE-4 (unknown off-nadir) retracking is used, the error in sea surface height, σ_{SSH}, increases as wave height increases (look at the southern ocean in next slides).

σ_{SSH} values shown in next slides are at 20 Hertz. Divide by 4.2 to get the precision in a 1-Hz averaged SSH.

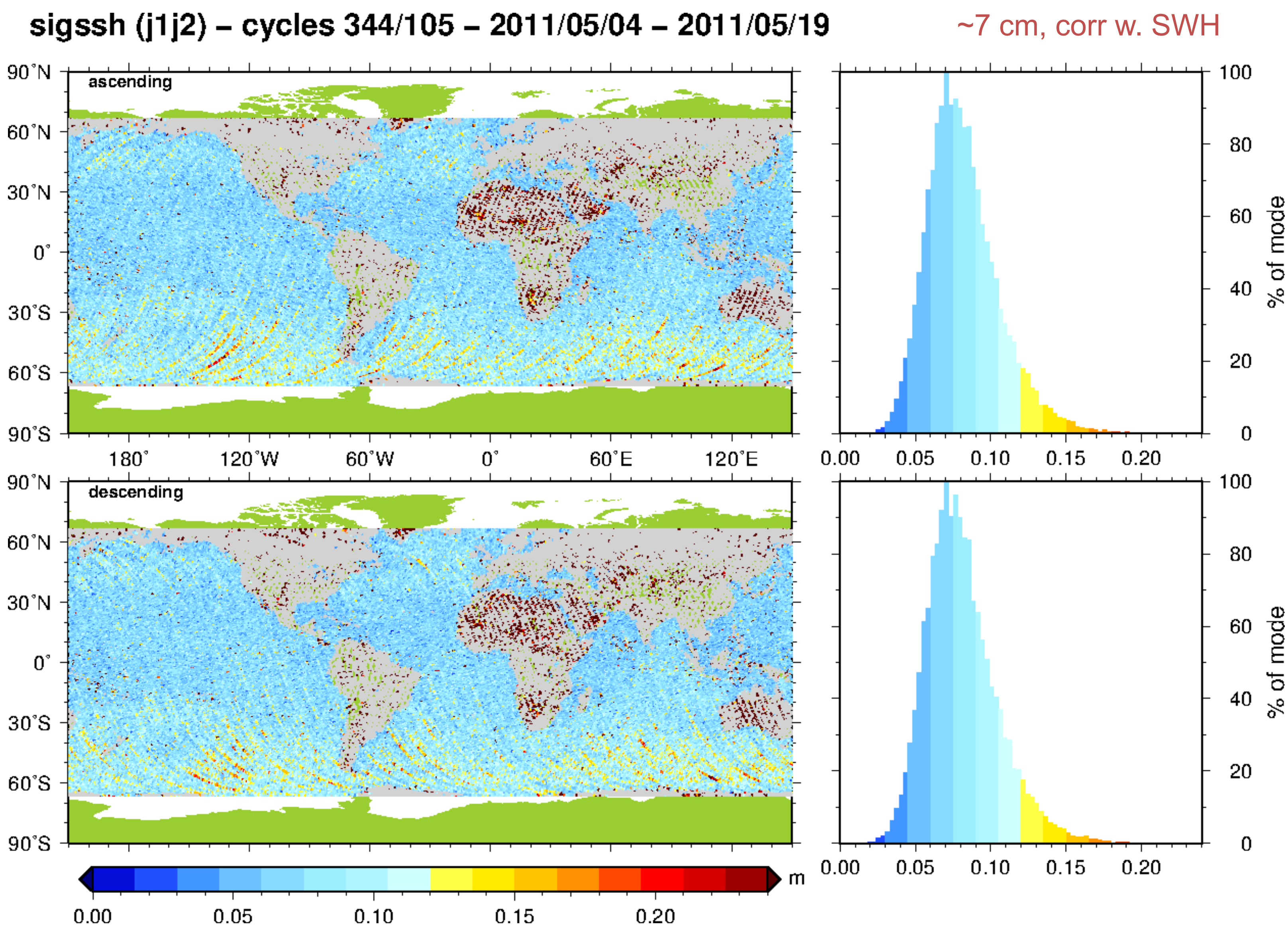
CS2 σ_{SSH} from MLE4 (ξ = free)

~6.5 cm, corr w. SWH



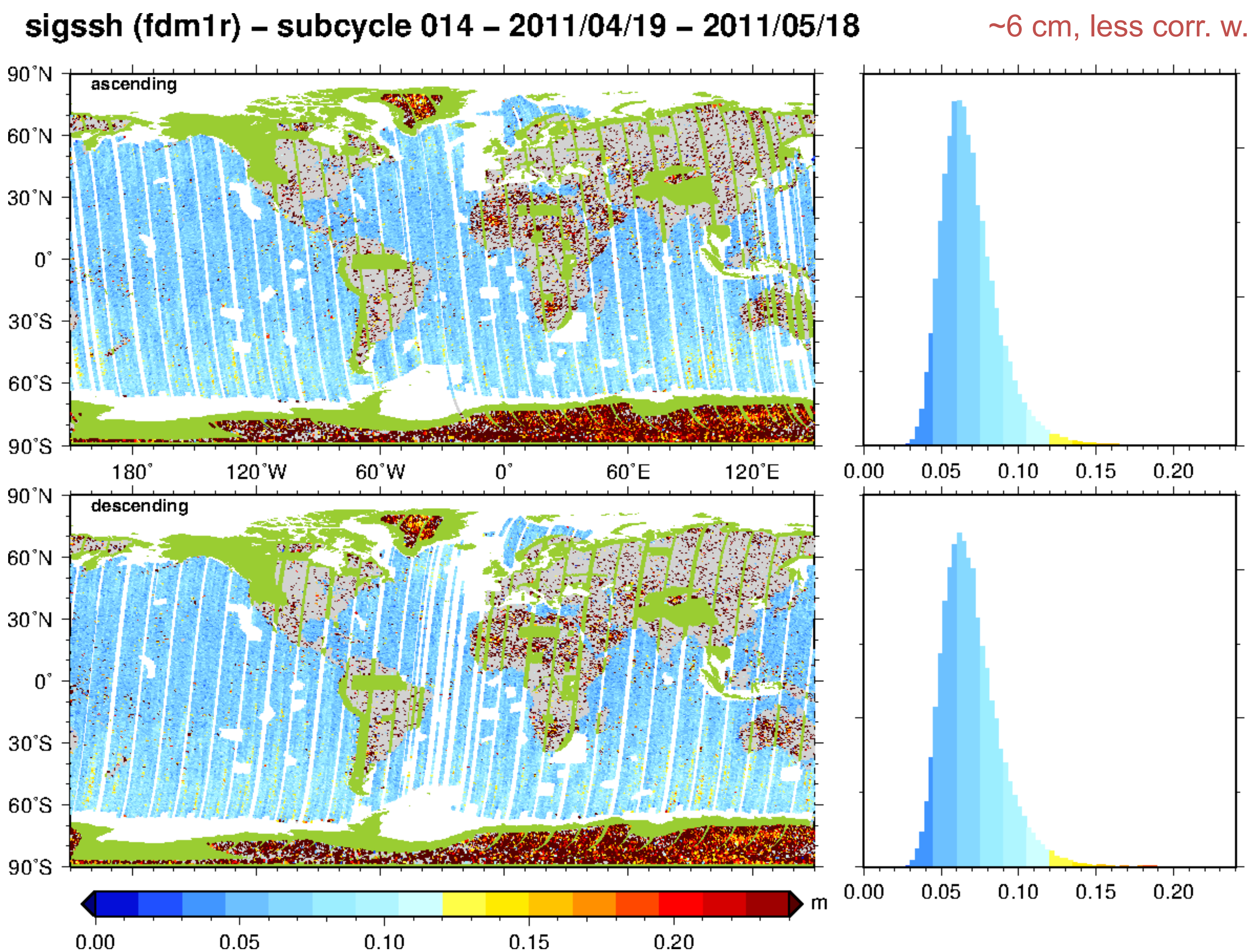
J-1&J-2 σ_{SSH} from MLE4

~7 cm, corr w. SWH



CS2 σ_{SSH} from MLE3 (ξ = known)

~6 cm, less corr. w. SWH



Platform attitude biases

Off-nadir angle estimated by retracker does not match spacecraft attitude data, suggesting small rotation between the coordinate systems of the antenna and the star trackers .

We fit a model for platform bias of the form

$\xi^2 = (\text{pitch} - \text{bias}_P)^2 + (\text{roll} - \text{bias}_R)^2$.

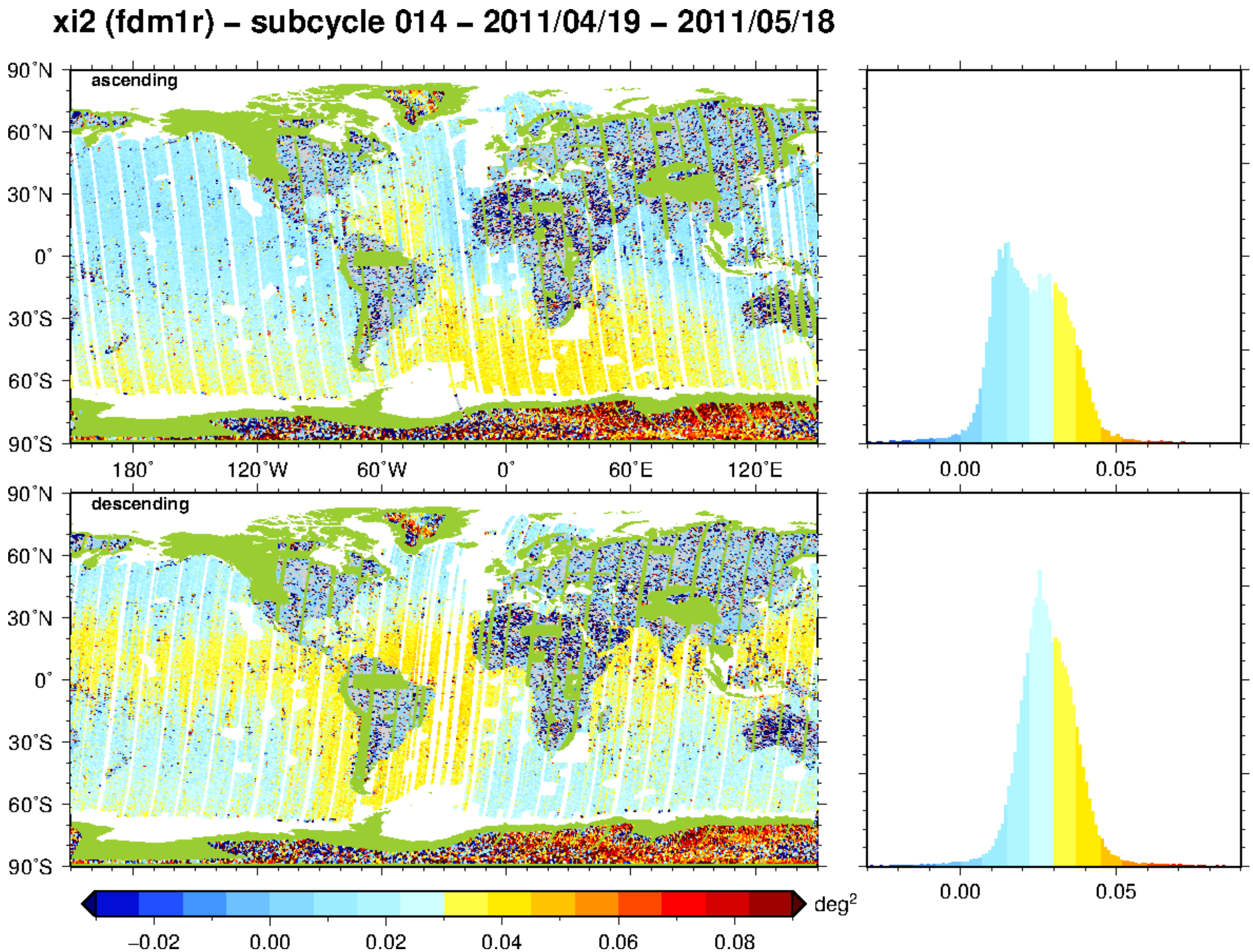
Assumptions: negligible thermal flexures; negligible biases between star trackers.

We estimate:

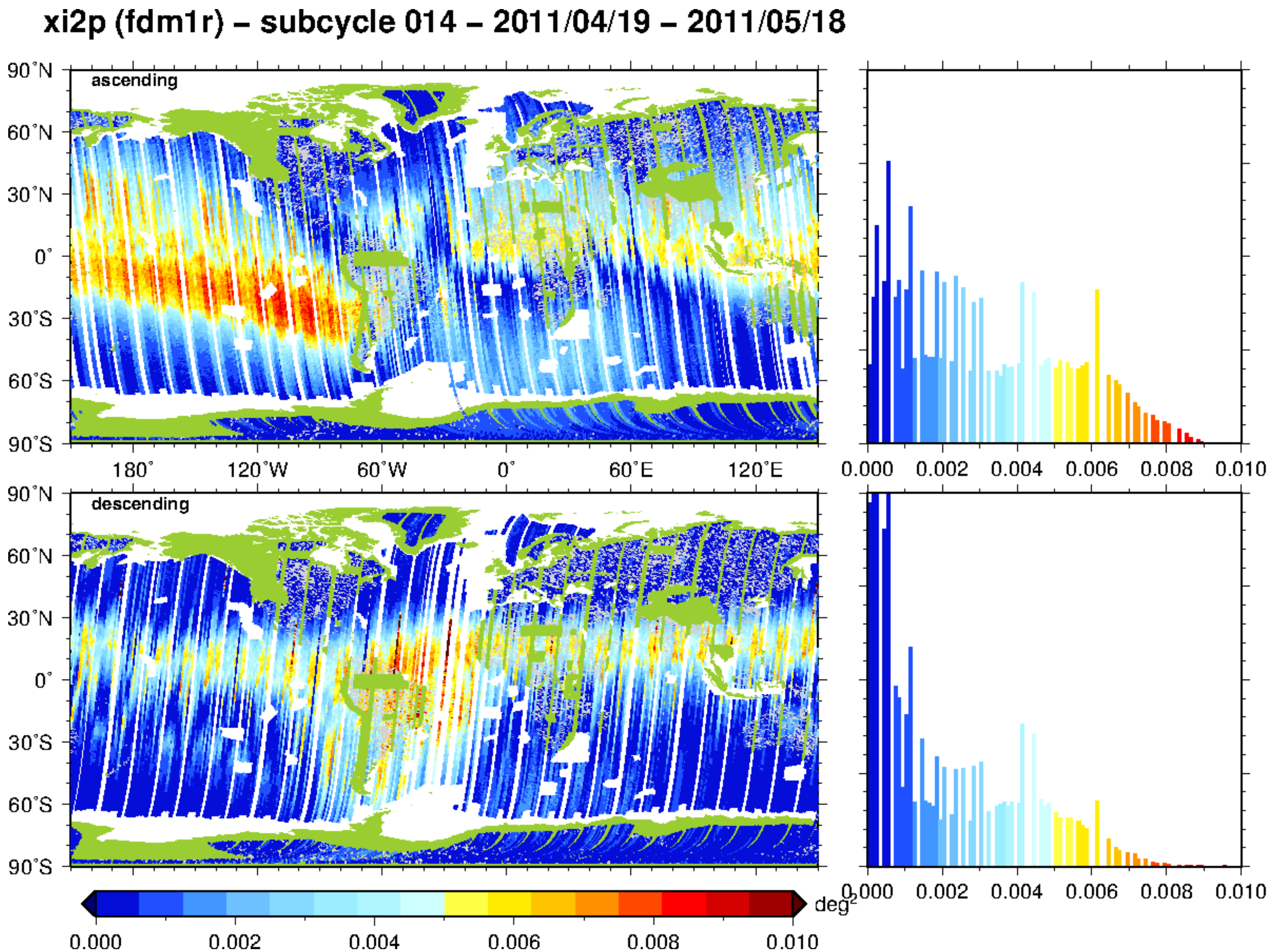
Pitch bias: +0.0962 degrees.

Roll bias: +0.0848 degrees.

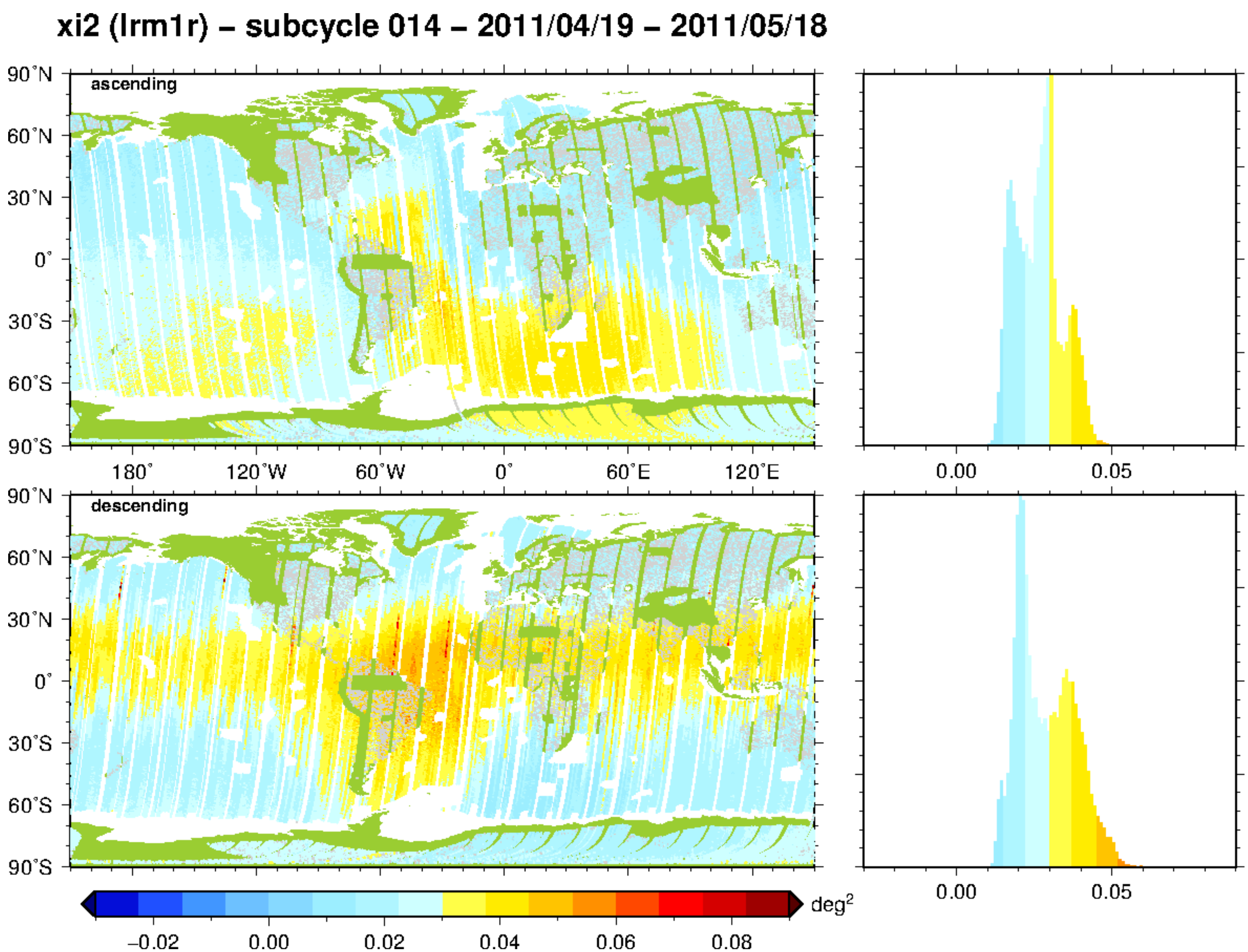
CS2 ξ^2 from retracker (MLE4)



CS2 ξ^2 from star trackers



CS2 ξ^2 from stars w/ bias adjusted



Conclusions

CryoSat2 is an excellent altimeter for oceanography. We thank ESA for the FDM L1b Product.

We are producing SWH, σ^0, U_{10}, and SSH by retracking LRM FDM L1b waveforms, adding the DORIS MOE orbit and ancillary corrections. We thank CNES for the MOE.

Our product compares well with J1, J2, E, though there are *ad hoc* values that could be tuned.

Range precision of CS2 appears superior to J1&2 when both are retracked with MLE4. Using known platform attitude and MLE3 further improves estimates.

We can make our product available as a NetCDF GDR or through RADS, as desired.

Thank you!

Additional back-up slides follow.

Elliptical antenna pattern

Classical "Brown model" theory for the expected waveform shape assumes a circular antenna pattern.

CryoSat2's antenna pattern is slightly elliptical.

If we average CS2's beam width over all azimuths, then the azimuthally averaged half-power beam width is the harmonic mean of the major and minor elliptical HPBWs.

We retrack CS2's waveforms with a circular beam theory using the azimuthally averaged HPBW.

This is a good approximation for conventional LRM waveforms.

This would be wrong for SAR/SARIN waveforms.

Wingham & Wallace [2010] have developed the full theory for the elliptical antenna. Their paper supports our belief that the circular approximation is a good one in our case.

Retracker options

Retracker allows selection of any or all of these parameters to be fitted:

1) Epoch, x_0
2) Width, s
3) Amplitude, A
4) Mispointing, $\kappa(\xi^2)$, ξ is off-nadir angle
5) Noise level, N

Any of these can be free parameters to be fitted, while others are held fixed.

$\kappa(\xi^2)$ can use 0th, 1st, or 2nd order approximation of Bessel function $I_0(z)$.

$I_0(z) = 1$, [MacArthur]

$I_0(z) = \exp(z^2/4)$, [Rodriguez]

$I_0(z)$ = two terms in exp() [Amarouche et al.]

Example:
"MLE3" would be first 3 parameters, and 1st order approximation.
"MLE4" would be first 4 parameters, and 2nd order approximation.
"RED3" would be first 3 parameters, 1st order approximation, and fewer gates fitted.

Retracker search features

Retracker iterative search requires these steps:

1) Initialization (by given or default values)
2) Interative update using Modified Gauss-Newton steps
3) Stopping criteria for success and failure

Initialization can supply "known" values (e.g., *off-nadir angle given from star trackers*, or along-track smoothed prior estimates, as in Sandwell & Smith two-pass method).

Iteration is solved by QR decomposition of column-balanced Jacobian (MLE3&4 use QR with column pivoting).

Stopping criteria for success/failure (in unweighted case) are MLE-like (A^2-normalized change in Mean Quadratic Error < $5\text{x}10^{-4}$ for 3 iterations = success).

Example:
To behave as MLE3 or MLE4, initialize with default values and proceed as above.

Default initializations MLE-like

Initialization of search may default to these values:

1) Epoch, x_0: set to normal track point.
2) Width, s: set equivalent to SWH = 2 m.
3) Amplitude, A: set to Max(waveform)
4) Mispointing, $\kappa(\xi^2)$, ξ is off-nadir angle: set to $\xi = 0$.
5) Noise level, N: set to average of first five gates used.

For CryoSat2, we fit the middle 104 of the 128 gates, as is done also for Jason.
Laurent P. said in Coastal meeting we should make this 106 and 126, I think.

Making a guess at σ^0

Constant, unless raining

From Orbit

From Retracker

$$\ell\left(\frac{P_R}{P_T}\right) = \ell(\sigma_0) + C - \ell(L) - 30\log_{10}\left(\frac{h'}{h_N}\right) + \frac{10}{\ln(10)}\left[\frac{-4}{\gamma}\sin^2\xi + \frac{k_j s}{2}\right] + \ell\left(\frac{A}{A_N}\right) \tag{1.47}$$

Target Amplitude Maintained by AGC

in which

$$C = \ell\left(\frac{c\pi\lambda^2 G_0^2 A_N T}{(4\pi h_N)^3\,\eta}\right) \tag{1.48}$$

σ^0 is mainly given by a constant, *C*, (+/-?) AGC (is AGC an amplification or an attenuation?) (AGC or 62 – AGC ?). Retracking yields small (< 1 dB) corrections to apply to refine σ^0. We had to guess the system constant, *C*, and get the sign right, in order that the histogram would not be inverted.